Low-light divergence in photovoltaic parameter fluctuations

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We study statistics of the major photovoltaic (PV) parameters, such as open-circuit voltage, short-circuit current, etc., versus light intensity on a set of nominally identical thin-film CdTe/CdS solar cells. A crossover light intensity is found, below which the relative fluctuations of the PV parameters diverge inversely proportional to the square root of the light intensity. We propose a model in which the observed fluctuations are due to lateral nonuniformities in the device structure. The crossover is attributed to the lateral nonuniformity screening length exceeding the device size. From the practical standpoint, our study introduces a simple uniformity diagnostic technique. [DOI: 10.1063/1.1563836]

It was found in recent years, that thin-film photovoltaics demonstrate a considerable degree of lateral nonuniformity. Examples are variations in surface photovoltage, (ranging from 0.2 to 0.7 V)[1] and areas of reduced photovoltaic activity[2] in $Cu(In,Ga)Se_2$ polycrystalline devices. For CdS/CdTe photovoltaics, optical beam[3,4] and electron-beam-induced current[5,6] showed strong inhomogeneities of the length scales greater than the grain size. Nonuniformities were also found in recombination lifetime,[7] photoluminescence,[8] voltage mappings,[9] in CdTe, a-Si:H,[10,11] and multicrystalline silicon.[12–14] It was shown[15,16] that local shunts of a diode nature could dominate the forward current, and that lateral nonuniformities cause current losses and degradation.[17–19]

One known effect of nonuniformities is that nominally identical devices can have different parameters. It is not unusual, indeed, to observe ~10% variations in the photovoltaic (PV) parameters between two cells ~1 cm apart on a substrate. Also, it has been a longstanding folklore that variability between nominally identical devices increases as the light intensity goes down. In this letter, we show how lateral nonuniformity leads to device parameter variability and how it becomes more visible under low light, which may be used to screen out ''bad'' cells.

In our characterization, a device current–voltage curve ($J-V$) is described by a set of standard parameters: open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), fill-factor (FF), open-circuit and short-circuit resistances (R_{oc} and R_{sc},) illustrated in Fig. 1. The ideal-diode model,

$$J=J_0\left[\exp\left(\frac{eV}{nkT}\right]-1\right)-J_{sc},V_{oc}=\frac{nkT}{e}\ln\left(\frac{J_{sc}+J_0}{J_0}\right), \quad (1)$$

predicts J_{sc} linear and V_{oc} logarithmic in the light intensity I.[20] J_0 and n are the model parameters; other quantities have their standard meaning. R_{oc} and R_{sc} are typically determined by the factors beyond the model. In particular, shunting reduces R_{sc} and increases R_{oc}.

Following interpretation in Fig. 1, we relate the observed fluctuations to random shunts of ohmic or nonohmic nature. We tried to make the shunts more or less visible by varying their screening length[17]

$$L=L_0\sqrt{1+\frac{e|u|}{kT}},\ \ L_0\equiv\sqrt{\frac{kT}{e\rho j_0}}, \quad (2)$$

where j is the short-circuit current density and ρ is the cell-electrode sheet resistance. Its physical meaning is that the electric potential fluctuation u is balanced by the resistive potential drop $j_0L^2\rho$. The minimum screening length L_0 varies over a wide range. In our standard cells, $L_0\approx 3$ mm under $I=1$ sun, and $L_0\approx 3$ cm under $I=0.01$ sun. However, it was made 10 times shorter by applying a high-resistance electrode. We were able to cover the whole range from $L/d\ll 1$ (shunts are screened) to $L/d\gg 1$ (shunts span over the cell), where $d=1.1$ cm is the cell diameter.

More specifically, we studied 180 standard CdS/CdTe cells made as described in Refs. 8 and 17. These cells are thin-film junctions sandwiched between two electrodes, of which one is the transparent conductive oxide (TCO, $\rho=15\ \Omega/\square$) and the other is a metal of negligibly small resistance. In addition, we studied 72 high-resistive-electrode (HRE) cells where as a metal we used 5-nm-thick Cr layers of $\rho\sim 1.2\ k\Omega/\square$. (Cr sheet resistance is nonlinear in the

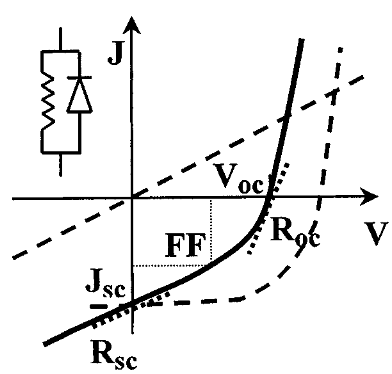

FIG. 1. $J-V$ characteristic of a shunted photovoltaic cell. Inset: the equivalent circuit. Dashed lines show the ideal diode and the ohmic shunt characteristics. The intercepts and the corresponding tangents represent V_{oc}, R_{oc}, and J_{sc}, R_{sc}. FF is the ratio of the power $\max\{VJ(V)\}$ (dotted rectangular) to the product $J_{sc}V_{oc}$.

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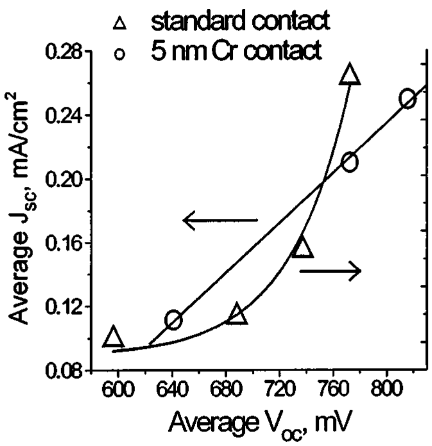

FIG. 2. Average J_{sc} vs average V_{oc} for the standard and HRE cells.

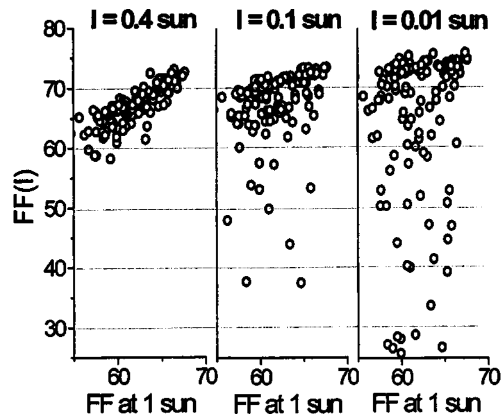

FIG. 4. Correlation between the values of cell FF under 1, 0.1, and 0.01 sun illuminations in the ensemble of 130 standard contact cells.

above thickness range[21]). Such cells are similar to the standard ones, except that TCO plays the role of the low-resistance electrode.

Shown in Fig. 2 the average cell V_{oc} versus J_{sc} dependences are, respectively, exponential and linear for the standard and HRE cells. The difference is understood in the terms of sheet resistance. For the standard contact ($L/d \gg 1$), the current is collected from the entire cell and is proportional to the light intensity, which, in accordance with Eq. (1), is exponential in V_{oc}. For the HRE cells ($L/d \ll 1$), the ohmic losses make it impossible to collect current from the entire cell. The majority of the HRE cell remains effectively under open circuit, hence $J=(V-V_{oc})/\rho$ (Fig. 3).

The fluctuations in the cell parameters increase as the light intensity decreases (see Fig. 4 for FF; other parameters behave similarly). In particular, the correlation between 1 and 0.01 sun FFs fails almost completely. More quantitatively, the fluctuations are characterized in Fig. 5. They diverge below certain crossover light intensity $I_c \sim 0.1$ sun. Unlike the data in Figs. 4 and 5, the HRE cell fluctuations were suppressed.

In addition we compared the parameter fluctuations between different cells, on the one hand, and between different spots (2 mm apart) on the same cell, on the other hand. For the HRE cells the former and the latter statistics appear undistinguishable; hence, spots 2 mm apart represent effectively different devices, which is consistent with $L/d \ll 1$. To the contrary, the intracell fluctuations were not detected in the standard cells.

We have found strong correlations between the fluctuations in V_{oc}, FF, and R_{oc}. Following the interpretation in Fig. 1, this suggests random shunts to be the cause for the observed fluctuations. The lack of correlation between the above parameters and R_{sc} implies that these shunts are not ohmic.

The L/d ratio is an important parameter explaining the crossover intensity in Fig. 5 and the differences between the standard and HRE cells. We attribute the crossover light intensity I_c to the condition $L=d$. Indeed, for the standard cells with $j=20$ A/cm^2, Eq. (2) predicts $L_0=d$ at $I=0.1$ sun close to the crossover in Fig. 5. Implicitly, this suggests weak ($|u| \leq kT/e$) nonuniformities with $L \approx L_0$. The estimate $L \approx L_0$ also explains our observations for HRE cells: fluctuation suppression ($L \ll d$) and statistical independence of neighboring spots in a cell ($L < 2$ mm).

To quantitatively describe the fluctuation divergence in Fig. 5, we proceed from the fact,[8,17] that a point lateral nonuniformity causes the electric potential scaling as $\delta\varphi(r/L)$ with the coordinate r. The corresponding microcurrent then becomes $\delta \mathbf{j} \propto \nabla \delta\varphi \propto L^{-1}$. When $L/d \ll 1$, the current fluctuation felt by the probe is $\delta J \approx \delta j \sqrt{N} \propto L^{-1} L = \mathrm{const}(I)$, where $N \propto L^2$ is the number of shunts in the active area (see Fig. 3).

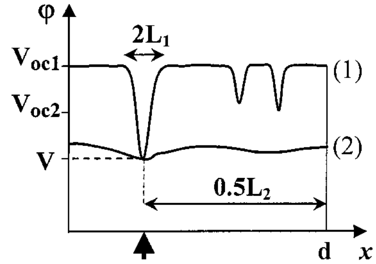

FIG. 3. Electric potential distribution along the resistive electrode, which is the TCO for the standard cells and 5-nm Cr contact for the highly resistive electrode cells. The measuring probe (fat arrow) applies voltage bias V. The cases of (1) large and (2) small cells are shown. For illustration purposes, the cell is uniform to the left of the probe and nonuniform to the right of it. In the case (1) the nonuniformities are screened and do not affect the current collection, as opposed to the case (2) in which they compete for the current with the probe.

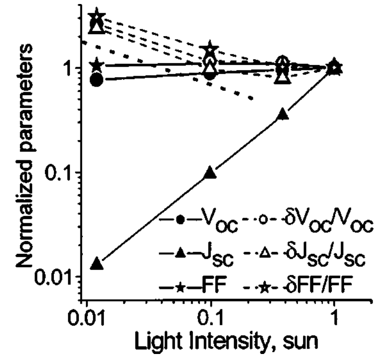

FIG. 5. The average $P-V$ parameters of open-circuit voltage V_{oc}, short-circuit current J_{sc}, and FF (solid symbols and lines), and their relative standard deviations (open symbols, dashed lines) versus light intensity normalized to the respective values at 1 sun and measured for an ensemble of 130 vapor transport deposited cells. Note the logarithmic scale: the standard deviations increase by a factor of 3 as the light intensity decreases by a factor of 10. The dotted line shows the predicted slope of the light intensity to the power -0.5.

Because the average current is logarithmic in intensity as was explained earlier, the relative current fluctuation is practically independent of the light intensity: $\delta J/J \approx \mathrm{const}(I)$ when $L/d \ll 1$. In the low-light regime $(L/d \gg 1)$, the number of shunts N does not depend of L and is determined by the entire device area, while J is proportional to the light intensity. This yields $\delta J/J \propto 1/LI \propto 1/\sqrt{I}$.

It is straightforward to extend the above argument to the parameters V_{oc} and FF. We note that $V_{oc} \propto \ln J$, and thus $\delta V_{oc}/V_{oc} \propto \delta J/J \ln J \approx \delta J/J$. FF is sensitive to fluctuations in both the current and the potential. Although the exact dependence is not known, one can write in the first approximation $\delta \mathrm{FF}/\mathrm{FF} \approx \delta J/J + \delta V_{oc}/V_{oc}$. Thus,

$$\frac{\delta V_{oc}}{V_{oc}}, \frac{\delta J_{sc}}{J_{sc}}, \frac{\delta \mathrm{FF}}{\mathrm{FF}} \propto \begin{cases} I^{-1/2} & \text{for } I \ll I_c \\ \mathrm{const} & \text{for } I \gg I_c \end{cases}. \tag{3}$$

The latter dependence is in excellent agreement with the data in Fig. 5. In addition we verified that the relative fluctuations in FF are approximately twice as large as that of J and V_{oc}.

In conclusion, low light is shown to reveal nonuniformities that are masked under standard illumination. A crossover light intensity is observed, below which the relative device parameter fluctuations increase as inverse of the square root of the light intensity. The relationship between the device parameter fluctuations and nonuniformity depends on the L/d ratio of the nonuniformity screening length to the device size, which makes nonuniformity effects size dependent. Our findings justify the low-light diagnostic techniques to screen out originally nonuniform devices.

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